STATUS OF SOIL ELECTRICAL CONDUCTIVITY STUDIES BY CENTRAL STATE RESEARCHERS

C. K. Johnson, R. A. Eigenberg, J. W. Doran, B. J. Wienhold, B. Eghball, B. L. Woodbury

ABSTRACT. *Practical tools are needed to identify and advance sustainable management practices to optimize economic return, conserve soil, and minimize negative off-site environmental effects. The objective of this article is to review current research in non-saline soils of the central U.S. to consider bulk soil electrical conductivity (EC_a) as an assessment tool for: (1) tracking N dynamics, (2) identifying management zones, (3) monitoring soil quality trends, and (4) designing and evaluating field-scale experiments. The interpretation and utility of EC_a are highly location and soil specific; soil properties contributing to measured EC_a must be clearly understood. In soils where EC_a is driven by NO_3-N, EC_a has been used to track spatial and temporal variations in crop-available N (manure, compost, commercial fertilizer, and cover crop treatments) and rapidly assess N mineralization early in the growing season to calculate fertilizer rates for site-specific management (SSM). Selection of appropriate EC_a sensors (direct contact, electromagnetic induction, or time domain reflectometry) may improve sensitivity to N fluctuations at specific soil depths. In a dryland cropping system where clay content dominates measured EC_a, EC_a-based management zones delineated soil productivity characteristics and crop yields. These results provided a framework effective for SSM, monitoring management-induced trends in soil quality, and appraising and statistically evaluating field-scale experiments. Use of EC_a may foster a large-scale systems approach to research that encourages farmer involvement. Additional research is needed to investigate the interactive effects of soil, weather, and management on EC_a as an assessment tool, and the geographic extent to which specific applications of this technology can be applied.*

Keywords. *Electrical conductivity, Electromagnetic induction, Field-scale experiments, Geophysical sensors, Precision agriculture, Site-specific management, Sustainable management.*

Practical tools are required to identify, assess, and advance sustainable management practices as a means to optimize farm economics, conserve soil organic matter, and minimize negative environment impacts (Doran, 2002a, 2002b). Geophysical sensors for measuring bulk soil electrical conductivity (EC_a) may exemplify one such tool. Data from EC_a sensors can be interfaced with data loggers and Global Positioning Systems, and integrated using Geographic Information Systems, to produce spatial maps of EC_a. Comparison of these maps with soil tests, yield maps, and other sources of information may be useful for addressing a variety of agronomic sustainability issues.

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The wide-ranging and diverse utility of EC_a is a function of the soil properties contributing to its measurement and the significance of these properties to numerous commercial, environmental, and research objectives. Measured EC_a is the product of both static and dynamic soil factors, including salinity, clay type/percentage, bulk density, water content, and temperature (Rhoades et al., 1989). The magnitude and spatial heterogeneity of EC_a in an individual field are generally controlled by only one or two of these factors, which can vary from field to field. For this reason, the derivation, significance, and utility of measured EC_a are highly location and soil specific.

Soil clay content dominates measured EC_a in most farm fields in the central U.S. (Veris Technologies, 2003). Hence, EC_a has been used to predict depth to claypan (Kitchen et al., 1999) and map spatial variations in soil texture (Williams and Hoey, 1987). In these texture-driven systems, sequential maps of EC_a remain consistent because variations in dynamic soil properties, temperature, and/or moisture affect only the magnitude of measured EC_a, not spatial patterns within a field (Sudduth et al., 2001). Methods have been developed to standardize EC_a for soil temperature (McKenzie et al., 1989).

In other agronomic and experimental settings, high levels of naturally occurring or fertilizer-derived salts in the soil solution can supersede texture as the principal driver of EC_a (Rhoades et al., 1989; Eigenberg et al., 1996). Sequential EC_a maps from salt-driven systems often exhibit significant fluidity, a reflection of the mobility of some salts in soil. These EC_a maps convey information very different from that of the more stable texture-driven systems. Applications include the use of EC_a to locate saline seeps (Corwin and

Rhoades, 1982) and track seepage patterns from feedlot lagoons (Ranjan et al., 1995).

Land management is also a factor in EC_a measurement. In non-saline soils of the central U.S., applied manure or commercial fertilizers can significantly influence EC_a, sometimes transforming texture- into salt-dominated systems. Image processing methods are being developed to partition EC_a into texture-associated (soil solid phase) and salt-associated (soil solution phase) components (Eigenberg and Nienaber, 1999). This is done by subtracting a baseline EC_a map, made prior to nutrient amendment, from sequential maps taken following fertilization. It is believed that the remaining EC_a reflects plant-available N, largely NO_3-N, which can be monitored for changes throughout the growing season.

Measured EC_a may or may not correlate with crop yields in a given location. The differences in correlation occur as a result of weather impacts on crop yields and soil properties that control EC_a but not yield (Kitchen et al., 1999). Yet, when the same soil properties underlie both EC_a and crop yields, EC_a maps provide an ideal basis for soil sampling schemes that depict spatial variability in production potential (Corwin et al., 2003; Johnson et al., 2001). Moreover, these maps provide information important for site-specific management (SSM).

The objectives of this article are to review the current status of EC_a research in non-saline soils of the central U.S. and to examine potential applications for EC_a in this region and beyond. Case studies will be considered within three categories: tracking N dynamics for SSM, classifying management zones, and designing and evaluating field-scale experiments. Experimental methods and findings will be summarized briefly with the understanding that interested readers can seek detailed information from cited publications specific to the case studies presented. This approach will be used to illustrate the value and versatility, as well as the limitations, of EC_a as a tool for monitoring and improving the economic and ecological sustainability of a variety of agricultural systems.

Materials and Methods

Three types of commercial instruments are currently available for measuring EC_a: direct contact, electromagnetic induction (EMI), and time domain reflectometry (TDR) sensors. Each of the experiments detailed in this article involved the use of one or more of these instruments. Direct contact sensors, such as the Veris 3100 Sensor Cart (Veris Technologies, Inc., Salina, Kansas), appear and function as small farm implements. They measure soil resistance to the flow of an electric current using three or more pairs of coulter electrodes that penetrate the soil surface approximately 6 cm. One pair of electrodes emits an electrical current into the soil, while the others detect decreases in voltage (resistance). The distance between emitting and receiving coulter electrodes determines the depth of EC_a measurement. Resistance (ohms) is converted to conductivity (mS m^{-1}) by a data logger as: 1/resistance = conductivity. For reporting purposes, EC_a is sometimes converted to dS m^{-1} by dividing mS m^{-1} by 100.

Direct contact sensors are well suited to use by farmers because they maintain calibration and are not affected by metal interference. These instruments can be pulled behind a pick-up or farm implement and, when used in combination with GPS, are ideal for EC_a mapping. They are not suitable for use in cropped fields (the exception being winter wheat and similar crops in the early stages of growth), and measurements of EC_a can be made only at predetermined depths, approximately 0 to 30 cm and 0 to 90 cm.

Non-contact sensors, including the EM-38 (Geonics, Ltd., Mississauga, Ontario) and the Dualem-2 (Dualem Inc., Milton, Ontario), are designed for point-source measurements or for evaluating small areas. They use EMI technology wherein soil response to a magnetic field, induced by a transmitter coil, is measured by a receiver coil. The EM-38 may be better suited for specific types of research than for application in production agriculture because it is prone to drift. In the Dualem-2, drift is reduced by positioning the transmitting and receiving coils further apart and using a fiberglass filament to diminish thermal distortion.

The EM-38 and Dualem-2 are highly affected by the presence of metal, and neither is commercially available on a mobile cart for EC_a mapping. However, non-metallic carts or sleds can be fashioned to cradle non-contact EC_a sensors, thereby allowing continuous EC_a mapping both across fields and within rows of growing crops. An EM-38 placed on the soil surface measures EC_a to a depth of approximately 0.75 m in the horizontal mode and 1.5 m in the vertical mode; thus, EMI sensors permit EC_a measurement at variable depths determined by the height of the instrument above the soil surface and whether it is positioned in the horizontal or vertical dipole mode. Because the transmitting and receiving coils in the Dualem-2 are farther apart than those of the EM-38, it integrates EC_a over a greater soil volume. Consequently, EC_a measurements are taken at approximate depths of 1.5 m in the horizontal mode and 3 m in the vertical mode. Vertical and horizontal operating modes of the EM-38 are determined by the physical orientation of the instrument, while the Dualem-2 records both horizontal and vertical signals simultaneously. The EC_a response, for direct and non-contact sensors, is believed to be biased toward the soil surface and to diminish with depth. The EM-38 and Dualem-2 produce highly correlated measurements of EC_a (Fritz et al., 1999).

Time domain reflectometry simultaneously provides information on volumetric water content and EC_a. Laboratory and field analyses indicate that these two parameters can be independently determined when using the same probe and volume of soil (Dalton, 1987; Dasberg and Dalton, 1985). Their measurement is based on the proportional relationship between soil water content and pulse transit time, the time it takes for a voltage pulse to travel down a soil probe and back (Topp et al., 1980). Dalton et al. (1984) derived an equation for bulk soil electrical conductivity expressed in terms of the ratio of transmitted voltage to reflected voltage, probe length, and the dielectric constant of the media. Because TDR instruments are stationary, they are not useful for producing EC_a maps of large areas. However, TDR offers two advantages over other EC_a technologies: simultaneous assessment of EC_a and volumetric water content, and greater sensitivity to EC_a dynamics in surface soils.

Clearly, each of the methods for measuring EC_a (direct contact, EMI, and TDR) has advantages and disadvantages. The selection of one over another should be based on the intended use or experimental requirements and/or objectives.

Results and Discussion

Tracking N Dynamics for Site-Specific Management

Site-specific management is a spatially directed approach to soil, crop, and pest management based on the varying conditions within a field (Larson and Robert, 1991). Theoretically, SSM of N has both economic and ecological advantages over uniform application. By reducing N inputs in low-yielding parts of a field, economic loss is avoided and the potential for N contamination due to leaching and runoff is decreased (e.g., Harmel et al., 2004). In irrigated systems, site-specific N application will generally reduce the total amount of fertilizer applied to a field. In dryland systems, where farmers typically apply fertilizer at less than optimal rates, SSM will increase N inputs in high-yielding areas of a field to improve yield potential and economic return. In practice, spatially and temporally appropriate nutrient amendment is very difficult to achieve. Improved understanding of soil-crop dynamics and their response to applied N is essential for SSM.

In saline soils or soils containing significant amounts of both NO_3-N and NH_4-N, the utility of EC_a as a tool for tracking N dynamics is questionable. Because NO_3-N is highly mobile compared to NH_4-N, soils with the same mineral-N concentration will produce different EC_a measurements depending on the relative amounts of NH_4-N and NO_3-N present. However, in the non-saline soils of the central U.S. considered in this article, NH_4-N is quickly denitrified to NO_3-N. Concentrations of NH_4-N are typically low, except under rare conditions where soils are cool and anaerobic. In case studies I through III, it is important to note that NO_3-N is a primary driver of EC_a, while NH_4-N and other electrolytes are minor contributors to its measurement.

Case Study I

A study was initiated in 1992 at the U.S. Meat Animal Research Center, in south-central Nebraska, to assess the long-term impacts of beef feedlot manure application (composted and non-composted) on nutrient movement and accumulation in the soil. Beef cattle manure contains nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, sodium, chloride, iron, and other trace minerals that produce average EC_a values in the range of 3.7 dS m^{-1} (Gilbertson et al., 1975). In soil, average EC_a ranges from below 0.1 to 1.1 dS m^{-1} in non-saline/coarse and very saline clay soils, respectively (Smith and Doran, 1996). Applied beef manures would be expected to elevate soil EC_a, and EC_a methods have been shown to be sensitive to areas of high nutrient levels (Eigenberg et al., 1996).

This study was undertaken to assess the EC_a dynamics during the corn (*Zea mays* L) growing season in manure, compost, and fertilizer treatments with and without a winter cover crop (Eigenberg et al., 2002). Soils at the center-pivot irrigated site (244 × 244 m experimental field) are of silt loam texture (fine, montmorillonitic, mesic Pachic Argiustolls). Plots had four replications with two main treatments of cover (+CC) and without cover (-CC) using a rye (*Secale cereale* L.) winter cover crop. Five subplot nutrient treatments included a fertilizer check at recommended N rates (NCK), and beef feedlot manure (MN, MP) and beef feedlot manure compost (CN, CP) at recommended N and P rates (Ferguson and Nienaber, 2000). In 1999, sequential EC_a maps were taken periodically throughout the growing season by EMI using an EM-38 in the horizontal dipole mode (approx. 0.75 m depth). The EM-38 was mounted and pulled through the field, on either a trailer or a sled, to allow continuous assessment of EC_a as the corn matured. Within 24 h of each EC_a survey, two 1.91 cm diameter soil cores (0 to 23 cm and 23 to 46 cm depths) were collected from randomly selected sites within each treatment. Soils were analyzed for total and organic N; KCL-extractable NO_3-N, NH_4-N, and NO_2-N; and soil pH and electrical conductivity (1:1 soil:water extracts). Soils were also sampled (15, 30, 60 90, 120, and 150 cm depths) and analyzed at the end of the growing season to detect potential leaching (Ferguson and Nienaber, 2000).

Measured EC_a became higher ($P < 0.05$) in manure and compost treatments, compared to fertilizer check plots, approximately 30 days after amendment application and remained higher until corn silking (fig. 1a). These differences disappeared statistically ($P < 0.05$) after DOY 180 when the crop was about 0.7 m tall. From DOY 180 through DOY 215 (corn silked), EC_a generally declined, corresponding to a period of rapid nutrient uptake by the growing crop. The EC_a would be expected to step to a higher level and remain elevated if the increase were due to non-macronutrient manure salts alone. This observed pattern suggests that soil nutrient dynamics were contributing to measured EC_a. Patterns in EC_a associated with the +CC and -CC treatments (fig. 1b) may also be explained by soil nutrient dynamics. Early in the growing season, some of the organic residue N was immobilized near the soil surface by the winter cover crop, resulting in a lower EC_a for +CC compared to -CC. Later in the growing season, immobilized N in +CC was mineralized, thereby entering the nutrient pool and resulting in convergence of the -CC and +CC curves (between DOY 180 and DOY 190). The EC_a values for the two treatments diverged again due to re-establishment of the fall cover crop and uptake of soil nutrients in the +CC treatment. These lower EC_a values were also associated with decreased concentrations of soil NO_3-N (Eigenberg et al., 2000), an indication of EC_a sensitivity to nutrient uptake by the rye. Ferguson and Nienaber (2000) found that the rye cover crop reduced NO_3-N leaching and accumulation in soil following the application of high rates of manure or compost.

Measured EC_a values were correlated with soil NO_3-N concentrations in the manure ($r = 0.48$ for 0 to 23 cm and $r = 0.79$ for 23 to 46 cm) and compost ($r = 0.48$ for 0 to 23 cm and $r = 0.86$ for 23 to 46 cm) treatments, applied at rates corresponding to crop requirements for N, when compared over the 18 surveys conducted in 1999. In the fertilizer check plots, correlations between EC_a and NO_3-N were weak or absent for surface soils (0 to 23 cm) but present at the deeper depth of measurement (23 to 46 cm). This is because the large volume of soil measured by an EMI instrument is quite stable compared with changes in the soil surface due to amendments, mineralization, and plant uptake. Significant correlations were also found between EC_a and soil water content, although these were not as strong as those between EC_a and NO_3-N.

Lack of correlation for the fertilizer check plot near the soil surface suggests that reduced soil organic amendments reduce soil N dynamics, which drive the correlation. Soil $EC_{1:1}$ measurements were taken in the spring (20 April) and again in the fall (9 Sept.) for all treatments. For the upper soil (0 to 23 cm), the $EC_{1:1}$ spring values were 0.67, 0.51, 0.32, 0.61, and 0.56 dS m^{-1} for MN, MP, NCK, CN, and CP,

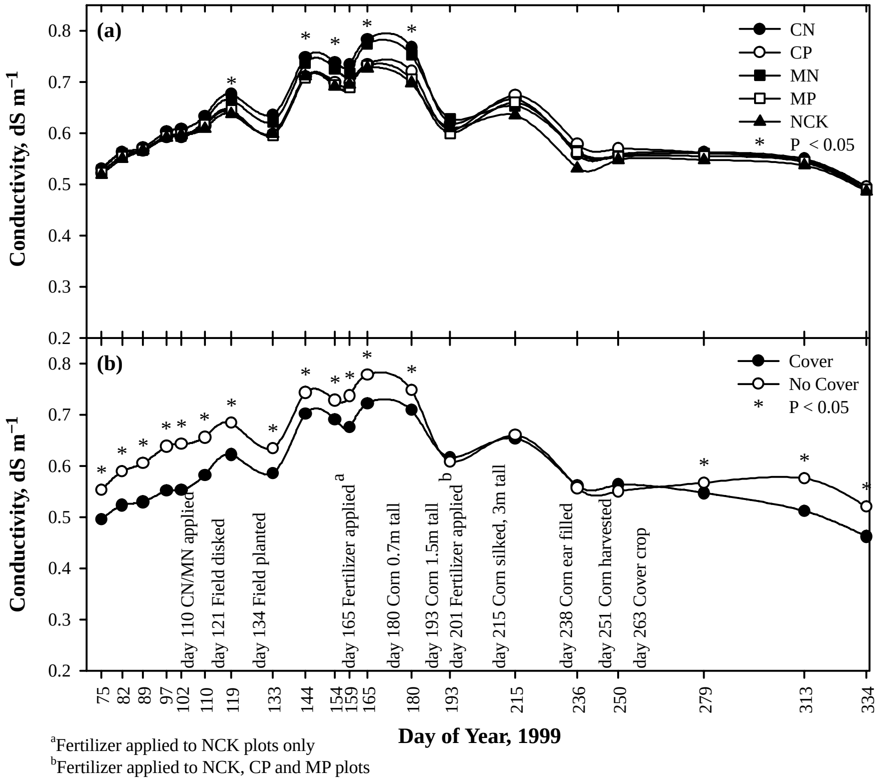

Figure 1. (a) Seasonal changes in bulk soil electrical conductivity (EC_a) as affected by manure (MN, MP), compost (CN, CP), and fertilizer N (NCK) for corn in 1999. Values plotted are the average for treatments with and without a rye winter cover crop. (b) Comparison of EC_a with and without a rye winter cover crop. Relevant management and corn growth stages are also indicated.

respectively. Fall values were 0.52, 0.28, 0.34, 0.50, and 0.35 dS m^{-1} for MN, MP, NC_K, CN, and CP, respectively. Differences between spring and fall are 0.15, 0.23, −0.01, 0.11, and 0.21 dS m^{-1} for MN, MP, NCK, CN, and CP, respectively. The upper soil (0 to 23 cm) of the fertilizer check plot showed very little change (−0.01 dS m^{-1}) between the start and the end of the season, compared to an average of 0.175 dS m^{-1} for the organic amendments. Correlations require corresponding changes in soil EC; the changes in soil $EC_{1:1}$ were less for the fertilizer check plot than for the corresponding organic amendments at the near surface depth.

In this study, sequential maps of EC_a effectively defined crop-available N dynamics before, during, and after the corn growing season. The EC_a surveys identified differences in manure, compost, commercial fertilizer, and cover crop treatments. These findings document the effectiveness of EC_a as an indirect measure for the spatial assessment of crop-soil interactions. Such a tool can potentially be used to determine cover crop performance, beef feedlot manure impact, and plant-nutrient interactions over a growing season. However, the EC_a procedure was more effective in tracking slowly mineralized organic nutrients than readily available inorganic nutrients.

Case Study II

Concentrations of inorganic N are most dynamic at the soil surface. This is due to removal of N by the crop and the fact that soil microbes responsible for N mineralization are fueled by surface residues and high concentrations of soil organic matter. For effective site-specific nutrient management, these N dynamics and their response to fertilizer inputs must be better understood. Ongoing experiments at the site described above (case study I) were designed to clarify near-surface dynamics of a manure-amended soil as measured by EMI using TDR techniques.

Field plot $EC_{a\ (TDR)}$ and $EC_{a(EMI)}$ data were collected using TDR and EMI, respectively, from approximately the middle of May until the first of November 2002. The $EC_{a(TDR)}$ data were collected every 15 min, with an average output every hour, and adjusted for temperature using a predetermined laboratory calibration for the probes. The $EC_{a(EMI)}$ data were collected weekly using a technique developed by Eigenberg et al. (2002) and were temperature compensated using an expression reported by McKenzie et al. (1989). A block of geostatistically determined $EC_{a(EMI)}$ values surrounding the TDR probes was averaged to limit plot spatial variability. Care was taken to remove $EC_{a(EMI)}$ data affected by the buried TDR cables and probes.

Probes were constructed in a three-rod design using 3.2 mm diameter stainless steel rods spaced 30 mm apart, with 12.5 cm of each rod left exposed. The TDR probes were inserted vertically 2 cm below the soil surface using a guide to ensure that the rods were parallel. Type-T thermocouple wires were installed at a depth of 15 cm to record soil temperatures. One probe was placed in the row of each treatment. Treatments were: compost, manure, and commercial fertilizer at the nitrogen rate (CN, MN, and NCK, respectively). Each of these treatments had cover crop (+CC) and no cover crop (-CC) subtreatments.

Correlation coefficients between $EC_{a(TDR)}$ and $EC_{a(EMI)}$ on EMI survey dates for each treatment are included in table 1, with seasonal plots shown in figure 2. Significant ($P < 0.05$) positive correlations were measured for all treatment combinations except the NCK (-CC) treatment.

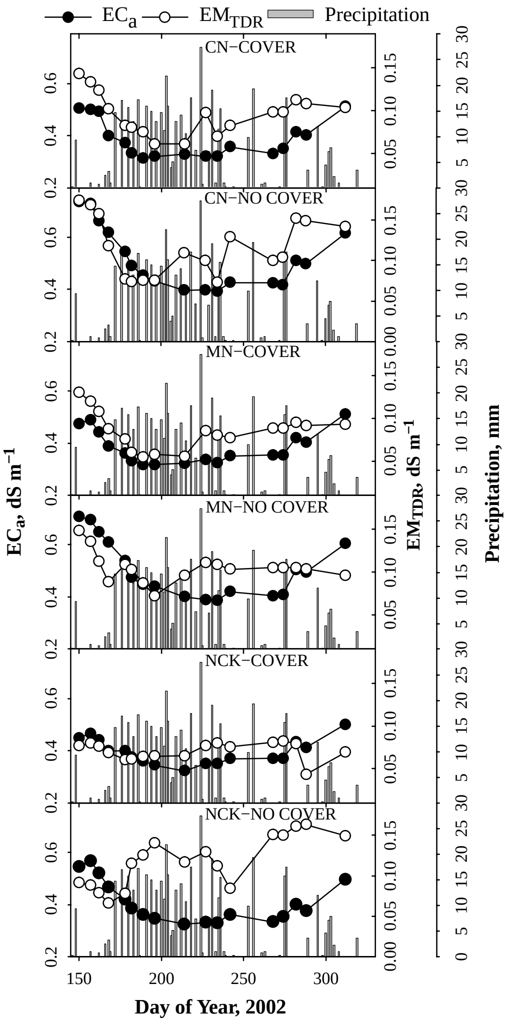

Figure 2. Apparent soil electrical conductivity (EC_a), bulk soil electrical conductivity (EC_{TDR}), and precipitation for compost, manure, and commercial fertilizer at the nitrogen rate (CN, MN, NCK, respectively) with cover crop (+CC) and no cover crop (-CC) treatments for the 2002 growing season. EC_{TDR} values are shown only for EMI survey dates.

The strongest positive correlations were for CN (+CC) and MN (+CC), and correlations for the (+CC) treatment were much stronger than for the (-CC) treatment (table 1). Both had P-values less than 0.0001, indicating that the broad soil surface effects measured by $EC_{a(TDR)}$ also influenced $EC_{a(EMI)}$. It is interesting to note that $EC_{a(EMI)}$ and $EC_{a(TDR)}$ for the -CC treatments were greater than those in the +CC treatments throughout most of the growing season (fig. 2). The fall-planted cover crop utilized nutrients that were mineralized after harvest. In the spring, this cover crop was destroyed and incorporated prior to planting, allowing soil moisture conditions among the treatments to equalize. It appears that uptake either by plants or microorganisms may have removed nutrients from the soil solution to mineralize this cover crop, thereby lowering the solution EC.

While $EC_{a(TDR)}$ and $EC_{a(EMI)}$ were positively correlated ($P < 0.05$) for the NCK (+CC) treatment, they were negatively correlated for the NCK (-CC) treatment (table 1). The $EC_{a(TDR)}$ and $EC_{a(EMI)}$ measurements followed similar trends in both NCK treatments (+CC and -CC) until the addition of nitrogen fertilizer on DOY 166 (fig. 2). Following fertilizer addition, $EC_{a(TDR)}$ increased while $EC_{a(EMI)}$ continued to decrease in both -CC and +CC treatments. However, the effect of fertilizer addition was more pronounced in -CC, where $EC_{a(TDR)}$ remained elevated for the remainder of the sampling period. The incorporated cover crop in the NCK treatment mineralized during the growing season in a manner similar to broadcast animal waste. Because fertilizer was concentrated in a narrow band between rows directly adjacent to the TDR probes in the NCK (-CC) treatment, $EC_{a(TDR)}$ was greatly influenced. On the other hand, the larger surface area used to calculate $EC_{a(EMI)}$ diluted the effect of the narrow concentrated band of N. Consequently, correlations between $EC_{a(TDR)}$ and $EC_{a(EMI)}$ were negative for the NCK (-CC) treatment. While there is no soil test data for verification, persistence of elevated $EC_{a(TDR)}$ could be a result of drought conditions and lower than expected yield, indications of decreased N uptake by the crop.

Table 1. Correlation coefficients for TDR and EMI measurements of electrical conductivity in treatments with and without a rye cover crop. Subtreatments include beef feedlot compost applied to correspond to crop requirements for N (CN), beef feedlot manure applied to correspond to crop requirements for N (MN), and fertilizer applied at the recommended rate (NCK).[a]

Treatment	Rye Cover Crop (+CC)	No Rye Cover Crop (-CC)
CN	0.831 *	0.714 **
MN	0.829 *	0.536 **
NCK	0.782 **	−0.482 ***

[a] *, **, and *** indicate significance at the 0.001, 0.05, and 0.10 probability levels, respectively.

Seasonal soil-crop EC dynamics measured by $EC_{a(EMI)}$ and $EC_{a(TDR)}$ were significantly ($P < 0.05$) correlated for all treatments except the NCK (-CC) treatment. This indicates that EMI-measured EC_a was controlled by ion dynamics in the upper 0.15 m of the soil surface and points to the potential application of EMI as a tool for evaluating soil-crop dynamics in manure-amended soils. While $EC_{a(TDR)}$ appears to be a more sensitive and accurate indicator of fluctuations in crop-available N derived from either surface-applied manure or commercial fertilizer, it is restricted spatially. Thus, EMI is more practical for precision field studies.

Case Study III

Nitrogen mineralized during the growing season is a significant contributor to crop N requirements. Information on this pool of N, as it varies across a field, is important for calculating N-fertilizer requirements in SSM. In non-saline soils, where NO_3-N is a dominant electrolyte in the soil solution, EC_a may be a cost- and labor-effective tool for estimating N mineralization early in the corn growing season. An irrigated experiment was undertaken at the University of Nebraska South Central Research and Extension Center near Clay Center, Nebraska, to evaluate the use of EC_a for this purpose (Wienhold and Rui, 2001). Soils at the site are a Hastings silt loam (Udic Argiustolls). The dominant electrolyte (25% to 35%) and primary contributor to measured EC_a is NO_3-N.

Comparisons were made between *in situ* measurements of N mineralization and N mineralization estimated from changes in EC_a. All analyses were made for three treatments, including soils amended with inorganic fertilizer, soils amended with manure, and non-amended control soils. *In situ* measurements of N mineralization were made by inserting 10 g nylon resin bags (A-464 DMB+ for trapping anions and C-249 IONAC+ for trapping cations, U.S. Filter, Rockford, Ill.) into the bottoms of aluminum tubes (4.8 cm diameter by 20 cm) containing soil cores (20 per plot). The tubes were reinserted in the soil and incubated under field conditions. During the growing season, four tubes per month were removed from each plot, and soils and resin bags were assayed for inorganic N.

An EM-38 in the horizontal mode was used to measure EC_a (approx. 0.75 m depth). Measurements were taken on four dates (5, 15, and 24 May and 27 June, 2000) early in the growing season. Changes in these temperature-corrected EC_a measurements were assumed to reflect NO_3-N dynamics in these non-saline soils. Thus, NO_3-N concentration was calculated by multiplying EC_a values by 140, and then by bulk density (1.3 Mg m^{-3}) and a depth factor, to convert to kg NO_3-N ha^{-1} depth of soil (Smith and Doran, 1996). Temporal changes in soil NO_3-N concentrations were fit to the first-order model (Stanford and Smith, 1972) to estimate potentially mineralizable N and a rate constant:

$$N = N_o(1 - e^{-kt}) \quad (1)$$

where

N = N mineralized (kg N ha^{-1}) at time t (weeks)
N_o = potentially mineralizable N (kg N ha^{-1})
k = rate constant ($weeks^{-1}$).

Calculated rate constants were then reinserted into the model to estimate NO_3-N mineralized during the growing season.

In situ measurements of N mineralization were highest in the manure treatment (66.4 kg N ha^{-1}), followed by the fertilizer (59.1 kg N ha^{-1}) and control treatments (47.3 kg N ha^{-1}). This seems reasonable given the increased availability of inorganic N and P for microbial decomposition of surface and soil residue in the amended soils, and the addition of easily decomposable organic matter in the manure treatment. During the first six weeks post-emergence, the first-order model rate constant calculated for manure-amended soils was almost twice that for the other two treatments, attributable to easily decomposable organic matter in the manure. Both N mineralization rates measured *in situ* and those estimated using EC_a showed similar separation among the three treatments (fig. 3). However, EC_a-estimated N mineralization was consistently lower: 16% less in the control, 26% less for fertilizer, and 17% less for manure treatments. Because N mineralization rates are highly temperature dependent, rate constants calculated early in the growing season likely underestimated later mineralization, but mineralization was even underestimated early on. It is assumed that the N mineralization model will improve with the inclusion of soil temperature effects.

Information on early growing-season N mineralization, provided by EC_a mapping, has significant potential application for SSM. For spring crops such as corn, maps of EC_a could be made at planting and 4 to 6 weeks later. Using image processing methods, temperature-corrected changes in EC_a could be used to estimate early growing-season N mineralization, but these estimation methods need refinement to better represent temperature effects. After subtracting applied and mineralized N from total crop N requirements (based on yield goals estimated from yield maps), the remaining N requirements could be calculated for side-dressing at spatially appropriate rates using a variable-rate applicator. Side-dressing N requires additional equipment and time in the field, which will increase costs. However, in many regions where groundwater is being contaminated by leaching of NO_3-N from agricultural fields, side-dressing is a recommended best management practice or a required practice.

Case Study IV

In the case studies above, EC_a was found to be a useful indicator of changes in soil nutrient dynamics, with NO_3-N being a major contributor (Eigenberg et al., 2002; Wienhold and Rui, 2001). However, this relationship does not hold true for all soils, locations, and depths of EC_a measurement. This study provides an example of weak to insignificant correlation between EC_a and soil N.

In 1998, a five-year experiment was initiated to examine the correlation between EC_a and NO_3-N concentrations in two distinctive soils in central Nebraska: an Ortello fine sandy loam (coarse-loamy, and mixed, mesic Udic Haplustolls), and a Hord silt loam (fine silty, mixed, mesic Cumulic Haplustolls). The experiment was designed as a randomized complete block with four blocks of four fertilizer application treatments, including site-specific manure, uniform manure, uniform commercial fertilizer, and a no-fertilizer check. Each year, 27 soil samples (0 to 15 cm) were taken at regular intervals from the middle of each treatment strip (12 × 670 m), air dried, and analyzed for organic C and soil N.

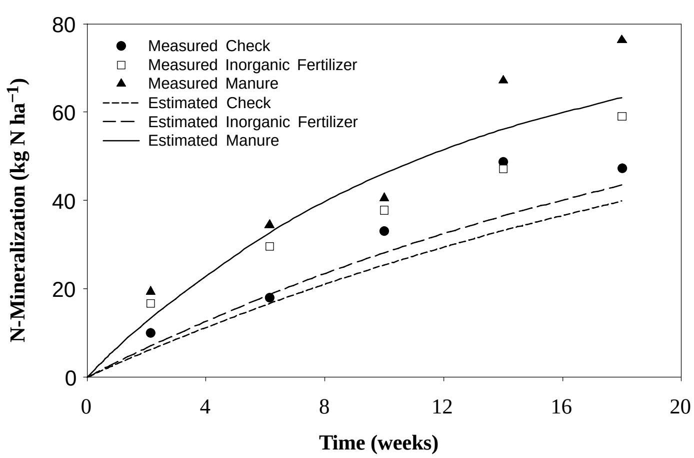

Figure 3. *In situ* N-mineralization and net mineralization predicted from bulk soil electrical conductivity.

Nitrogen was applied at rates targeting corn production levels of 10.7 Mg ha^{-1}. For the site-specific treatment, manure was applied to areas within the strips with soil C concentrations less than 1.4%. The first year after application, N availability was assumed to be 40% of total manure N (Eghball and Power, 1999). In subsequent years, N availability was determined by soil sampling for NO_3-N. For commercial fertilizer treatments, 10 kg P ha^{-1} was band applied at planting as liquid ammonium-polyphosphate starter fertilizer (10-24-0, N-P-K + Zn). The remaining N required was side-dressed as anhydrous ammonia (82-0-0) in June 1998 and pre-plant the last four years of the study.

Sequential EC_a measurements were taken by EMI between May and November. An EM-38 was used in 2001 (approx. depth of 0.75 m) and a Dualem-2 was used in 2002 (approx. depths of 1.5 and 3 m). Soil samples (0 to 30 cm depth) collected at the time of EC_a measurement were analyzed for NO_3-N and NH_4-N. Comparisons were made between EC_a and NO_3-N, NH_4-N, or NO_3+NH_4-N concentrations among the different fertilizer treatments to determine the utility of EC_a as an indirect measure for soil NO_3- or NH_4-N.

While EC_a distinguished among manure and non-manure treatments, as evidenced by differences in measured EC_a among treatments ($P < 0.05$), no consistent correlations were found between EC_a and soil inorganic N concentrations (table 2). Soil C had no effect on this relationship. It is possible that soil water content, as opposed to NO_3-N, may dominate measured EC_a in these sandy loam soils. Further research is required to determine the soil factors contributing to measured EC_a at this location.

MANAGEMENT ZONE CLASSIFICATION USING EC_a

Two general approaches can be taken for SSM of N in non-saline soils. The choice of one over the other will likely be determined by economic feasibility and the degree of within-field heterogeneity. In the first scenario, variable-rate applicators can continuously adjust rates in response to high-resolution data inputs. This approach was taken in case study III. A second scenario for SSM is to apply nutrients to management zones according to average requirements within each zone, a low-resolution basis. Management zones are created through a process called classification, the partitioning of soil into regions of similar production potential as a means to describe within-field variability. For a classification system to be effective for SSM, it should divide fields into zones delineating the same or similar yield-limiting factors (Lark and Stafford, 1997).

Case Study V

Management zones based on ranges of EC_a were identified and evaluated for potential application of SSM in winter wheat and corn at the Farm-Scale Intensive Cropping Study (FICS), a 250 ha dryland experiment in northeastern Colorado (Johnson et al., 2001; Johnson et al., 2003b). Mapped soils included Platner (fine, smectitic, mesic Aridic Paleustolls), Weld (fine, smectitic, mesic Aridic Argiustolls), and Rago loam (fine, smectitic, mesic Pachic Argiustolls). The contiguous experimental site was comprised of eight approximately 32 ha fields, with superimposed treatments that included two replicates of each phase of a no-till winter wheat (*Triticum aestivum* L.) - corn (*Zea mays* L.) - millet (*Panicum miliaceum* L.) - fallow rotation each year. Each field was mapped for EC_a, using a Veris 3100 Sensor Cart, when soils were near field capacity, and the maps were individually classified into four zones of EC_a: low, medium low, medium high, and high. The ranges of EC_a for each zone, across all eight fields, are given in table 3. Soil properties (0 to 7.5 cm and 0 to 30 cm depths), surface residue, and two years of winter wheat and corn yields from yield maps were evaluated for significant relationships to EC_a (0 to 30 cm depth) and partitioning among EC_a zones.

At the FICS, EC_a classification effectively delineated soil characteristics that define agronomic yield potential, essential requirements for zone-based soil sampling and SSM. Surface residue mass and soil properties related to yield

Table 2. Correlation coefficients for bulk soil electrical conductivity (EC_a) by electromagnetic induction and soil NO_3- and NH_4-N concentrations (0 to 30 cm depth) for 2001 and 2002.[a]

Date	Year	DOY	EMI Mode[b]	NO_3-N		NH_4-N		NO_3-N+NH_4-N	
12 June	2001	163	Horizontal	0.32		0.16		0.40	**
5 July	2001	186	Horizontal	0.34		0.12		0.26	
2 Aug.	2001	214	Horizontal	0.16		0.08		0.14	
30 May	2002	150	Horizontal	0.11		−0.15		0.004	
19 June	2002	170	Horizontal	0.35		0.10		0.27	
23 July	2002	204	Horizontal	−0.18		0.01		−0.15	
29 Aug.	2002	241	Horizontal	0.65	**	0.20		0.65	**
22 Nov.	2002	325	Horizontal	−0.01		0.85	*	0.29	
30 May	2002	150	Vertical	0.40		0.24		0.34	
19 June	2002	170	Vertical	0.37		0.30		0.35	
23 July	2002	204	Vertical	0.13		0.22		−0.07	
29 Aug.	2002	241	Vertical	0.53		0.32		0.58	
22 Nov.	2002	325	Vertical	−0.30		0.91	*	0.01	
30 May	2002	150	Vertical/Horizontal	−0.61	**	−0.71	*	−0.68	**
19 June	2002	170	Vertical/Horizontal	−0.28		−0.54		−0.39	
23 July	2002	204	Vertical/Horizontal	0.003		−0.45		−0.08	
29 Aug.	2002	241	Vertical/Horizontal	−0.21		−0.47		−0.33	
22 Nov.	2002	325	Vertical/Horizontal	0.88	*	−0.49		0.74	*

[a] * and ** indicate significance at the 0.05 and 0.10 probability levels, respectively.
[b] Horizontal indicates EC_a measurement using EM-38 (approx. 0.75 m depth) in 2001 and Dualem-2 (approx. 1.5 m depth) in 2002. Vertical indicates measurement using Dualem-2 (approx. 3 m depth) in 2002.

potential were negatively correlated with EC_a (r = −0.33 to −0.58), while soil properties associated with erosion were positively correlated (r = 0.37 to 0.50) (table 3). All of these properties were significantly different among EC_a zones ($P \leq 0.06$) at one or both soil depths. Whereas measured EC_a in case studies I through III was largely a function of soil NO_3-N concentration (derived from applied manure or fertilizer), clay content was the primary contributor to EC_a at the FICS, with bulk density playing a secondary role. Because the eroded (less productive) parts of each field were highest in clay content and bulk density, as surface EC_a increased, productivity decreased. This was substantiated by strong negative correlations between surface EC_a and winter wheat yields (r = −0.97 to −0.99). Due to the calcareous nature of soils at the FICS, eroded areas within fields exhibit increased concentrations of $CaCO_3$ and, hence, increased pH at the soil surface. For this reason, increased pH was indicative of soil erosion, and pH was positively correlated with EC_a. Conversely, the more productive soils in each field had lower amounts of clay at the surface and, therefore, lower EC_a. Since these soils were also characterized by higher levels of organic matter, water content, and nutrients, there was a negative relationship between surface EC_a and productivity. Increased soil water content and NO_3-N concentration are generally associated with increased EC_a. However, because EC_a is largely texture-driven at the FICS, soil water content and NO_3-N showed a negative correlation and no correlation with EC_a, respectively (Johnson et al., 2001).

The relationship between EC_a and yield can vary with both the crop being evaluated and the depth of EC_a measurement. For the FICS, there were strong correlations between yield and EC_a (0 to 30 cm depth) for wheat but not for corn. Lack of correlation between EC_a and corn yields is likely the result of severe drought-stress during critical periods in the growing season for both years of the study, an indication that weather factors can diminish the impact of soil factors on yield. However, while shallow EC_a (0 to 30 cm depth) described variability in wheat yields, deeper EC_a measurements (0 to 90 cm depth) correlated with yields of both wheat and corn. Moreover, the negative relationship between EC_a (0 to 30 cm depth) and wheat yields was reversed when wheat (and corn) yields were compared to EC_a at the deeper depth of measurement (0 to 90 cm). It is theorized that clay content becomes “background noise” at the deeper depth of EC_a measurement because the clay layer is encompassed within that depth in all parts of a field. Thus, within-field variations in deep EC_a may be determined by salts in the soil solution, which include N forms, and soil water content. Because these factors have a positive effect on yield, a positive correlation exists between wheat and corn yields, and deep EC_a.

For a specific crop in a specific field, yield data collected in an above-average year may serve as an indicator of maximum yield potential when expressed as a function of EC_a (fig. 4). A line falling at the 90th percentile of yield frequency can be used to identify yield goals, essential information for calculating nutrient inputs. In this semiarid system, EC_a management zones fulfill three requirements for SSM of wheat by serving as a basis for: (1) soil sampling to assess residual nutrients and soil attributes affecting herbicide efficacy, (2) yield-goal determination, and (3) prescription maps for metering inputs. In semiarid systems, where yield variability largely reflects the degree of drought stress, EC_a may be a more reliable basis for SSM across years than in higher precipitation regions, where both low and excessive moisture can limit yield. Further research is required to develop methods for calculating optimal herbicide and nutrients rates for different EC_a zones. By integrating other types of spatial information (yield, topographical, elevation maps, etc.) into the identification process, it may also be possible to improve the yield-prediction potential of management zones.

Designing and Evaluating Field-Scale Experiments

On-farm experiments conducted at the field-scale improve research relevance, promote a systems approach to experimentation, and encourage farmer participation, interest, and adoption of successful outcomes (Norman et al., 1998). It is important to evaluate such experiments with sustainability indicators that assess both soil physical, chemical, and biological response and crop yield response to management (Doran, 2002a, 2002b). However, these measures are taken at widely divergent levels of scale, and methods are needed for their comparison. Moreover, field-scale experimentation is often hampered by a lack of feasible replication, underscoring a need for alternative ways to estimate experimental error.

Case Study VI

Additional experiments were undertaken at the FICS (described in case study V) to evaluate the use of EC_a classification for integrating microbial-scale analyses of vesicular arbuscular fungi with sampling-site scale estimates of soil chemical and physical properties, and field-scale measures of crop yields from yield maps (Johnson et al., 2004). Microbial-scale soil analyses for the C16:1(*cis*)11

Table 3. Case study VI: Partial listing of soil properties (0 to 30 cm depth) including within-electrical conductivity (EC_a) zone means and significance across crop treatments, and correlation (r) with measured EC_a.

		Productivity-Associated Factors[a]						Erosion-Associated Factors		
	EC_a Ranges ($dS\ m^{-1}$)	Water content ($kg\ kg^{-1}$)	SOM ($Mg\ ha^{-1}$)	Total C ($Mg\ ha^{-1}$)	Total N ($Mg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	PMN ($kg\ ha^{-1}$)	Bulk density ($g\ cm^{-3}$)	Clay (%)	pH
EC_a zone[b]		**	*	*	*	*	**	***	**	*
Low	0.00 to 0.17	0.207	124.8	43.8	4.08	111.8	86.4	1.32	22.8	6.33
Medium low	0.12 to 0.23	0.187	115.9	35.2	3.45	69.2	67.0	1.39	24.3	6.42
Medium high	0.14 to 0.29	0.185	110.4	32.2	3.09	27.8	59.3	1.39	27.3	6.72
High	0.18 to 0.78	0.178	112.6	32.7	3.10	26.7	54.4	1.42	28.1	6.92
r values (P < 0.001)		−0.33	−0.34	−0.36	−0.38	−0.58	−0.50	−0.49	−0.50	−0.37

[a] SOM = total soil organic matter, P = extractable P, and PMN = potentially mineralizable NH_4-N.
[b] *, **, and *** indicate that comparisons of EC_a class treatments are significant at the 0.01, 0.05, and 0.10 levels, respectively.

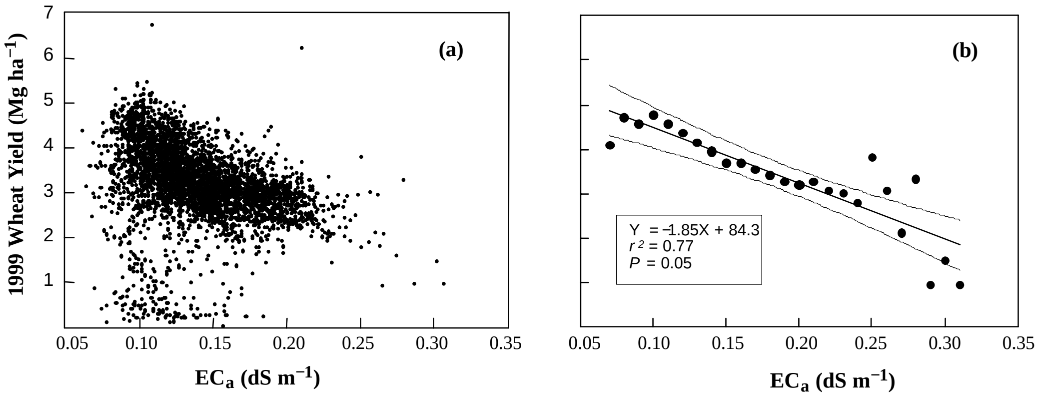

Figure 4. (a) Scatter plot of 1999 winter wheat yields from yield maps (two approx. 32 ha fields) as a function of bulk soil electrical conductivity (EC_a) (0 to 30 cm depth). (b) Boundary line of maximum yield, calculated using the 90th percentile of yield frequency for each 0.01 increment of EC_a, used to set yield goals for site-specific management.

fatty acid methyl ester biomarker and immunoreactive total glomalin (a glycoprotein produced by these organisms) were negatively correlated with EC_a (0 to 30 cm depth of measurement), positively correlated with soil productivity indicators (water content, organic matter, total C and N, extractable P, and potentially mineralizable N) and winter wheat yields, and significantly differently among EC_a zones ($P \leq 0.01$). Thus, EC_a-classified zones represent a point of reference through which microbial-, sampling site-, and field-scale data can be related. Repeated measurement of these sustainability indicators, over time, can be used to link microbial-scale findings to farm-scale economic and ecological outcomes.

Experiments at the FICS were also designed to evaluate novel means for statistically evaluating field-scale experiments. These included using: (1) within-field variability as a measure of experimental error in lieu of replication, and (2) EC_a-classified within-field variability as a basis for estimating plot-scale experimental error (Johnson et al., 2003a). To this end, mean-square errors were calculated for surface residue and soil properties measured at the FICS site using within-field variance. Comparisons between these estimates of experimental error and those derived from replication showed within-field variance to be an effective measure of experimental error for many parameters evaluated. At a 0 to 7.5 cm sampling depth, these included laboratory-measured EC, NO_3-N and NH_4-N, pH, extractable P, and microbial biomass. For the 0 to 30 cm depth, these included soil texture, water content, laboratory-measured EC, pH, extractable P, total C and N, microbial biomass C, and potentially mineralizable N. Thus, for some experimental objectives, within-field variance may serve as a surrogate for replication.

In the second approach for statistically evaluating field-scale experiments, surface residue and soil data collected at the FICS were compared with those from a nearby plot-scale experiment. The EC_a-classified within-field variance was shown to approximate plot-scale experimental error (fig. 5). These findings may provide alternative methods for statistically evaluating field-scale experiments.

CONCLUSIONS

The case studies included in this review illustrate both the versatility and limitations of EC_a as a tool for evaluating and implementing sustainable management practices in non-saline soils. Applications for EC_a span a broad range of sustainability issues, from tracking N dynamics in soil, and identifying management zones for soil sampling and SSM, to facilitating field-scale research. Yet, the results of these studies clearly show that “one size does not fit all” when

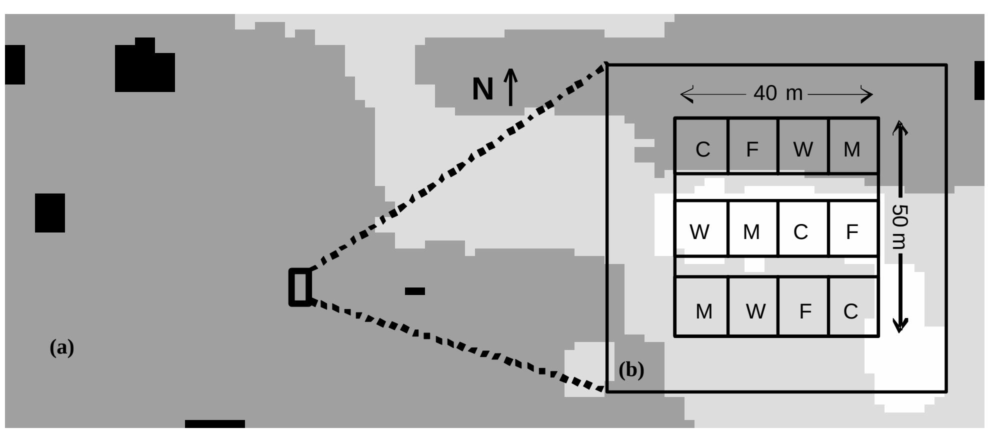

Figure 5. Relationship between bulk soil electrical conductivity (EC_a) and plot-scale blocking (replication): (a) an EC_a-classified map of an approximately 32 ha field at the FICS site, and (b) a typical plot-scale experiment identified within the field using EC_a classification as a basis for blocking. The W, C, M, and F labels represent any four treatments applied in a hypothetical plot-scale experiment.

applying EC_a. Measured EC_a can reflect spatial variation in crop yields, soil texture, organic matter, nutrient status, water content, any combination of these, or none of these. Furthermore, the correlation structure between EC_a, soil properties, and crop yields is not only soil specific; it can also differ among crops, with depth of EC_a measurement, and with weather variations during the growing season.

In evaluated non-saline soils, where EC_a is largely driven by soil NO_3-N concentrations and where NH_4-N concentrations are negligible, EC_a can be a useful scanning measure for assessing spatial and temporal variability in crop-available N. The labor, time, and cost benefits of such a method over traditional grid soil sampling are significant. Measured EC_a was shown to have sufficient sensitivity to detect variations in soil N dynamics occurring in response to manure and commercial fertilizer application and the presence of a winter cover crop. Furthermore, selection of the appropriate sensor can optimize EC_a sensitivity to N dynamics. Measurements using TDR are most sensitive and may be particularly useful for tracking N dynamics at the soil surface, but EMI responds well to NO_3-N deeper in the soil profile. While $EC_{a(TDR)}$ boosts accuracy and may benefit specific types of research, $EC_{a(EMI)}$ is a more practical tool for precision agriculture.

Surveyed EC_a also has the potential to rapidly assess N mineralization early in the growing season, information essential for calculating spatially appropriate fertilizer rates for SSM, but needs refinement to account for differences in soil temperature. It can also function as a monitoring device in post-harvest soils to detect the presence of excess NO_3-N susceptible to leaching and denitrification. It is important to note that EMI instruments assess a large volume of soil. Case studies I, II, and III indicate that, at least in some soils, the contribution of deep soil to measured EC_a is quite stable compared to that of surface soil, when surface soil is responding to amendments, mineralization, and plant uptake.

On the other hand, EC_a surveys (approximately 0 to 75 cm) of a sandy loam soil showed no significant correlation between EC_a and soil NO_3-N concentrations (0 to 30 cm depth), indicating that other soil factors dominate measured EC_a. This finding underscores the care that must be taken when generalizing EC_a-soil relationships. Prior to interpreting and applying EC_a maps for a specific purpose in a given soil and location, the soil properties driving measured EC_a must be first be identified and understood.

In non-saline soils where NO_3-N is not a significant contributor to measured EC_a, EC_a may still be a useful tool for SSM. In low-input dryland cropping systems, EC_a is often driven by soil clay content. In fact, these texture-dominated systems may show negative correlation or no correlation at all between EC_a and dynamic soil parameters usually associated with increased EC_a (i.e., soil water content and NO_3-N). Evaluation of one such system revealed that EC_a classification produces distinct management zones that delineate both soil characteristics associated with yield potential and actual wheat and corn yields from yield maps. These management zones can be used for yield-goal determination, soil sampling for residual nutrients, and metering inputs, three essential components of SSM. Additionally, analyses conducted on soil samples collected within management zones, over time, can be compared to monitor the impact of management on the soil resource.

Zone classification, based on EC_a, provides alternative bases for designing and evaluating field-scale experiments in dryland cropping systems. For some experimental objectives, within-field variance may be used as an estimate of experimental error in lieu of replication, and EC_a-classified within-field variance can be used to approximate plot-scale experimental error. Management zones based on EC_a also provide a pivotal point of reference through which microbial-, sampling site-, and field-scale data can be related. These unique applications for EC_a may encourage a large-scale systems approach to experimentation that fosters farmer involvement and interest in sustainable management practices.

Ultimately, the effectiveness of EC_a for a specific purpose in a specific location is determined by the degree to which soil factors governing EC_a measurement relate to the desired information or scientific questions being addressed. Continued research is required to further our understanding of relationships between EC_a, soil properties, and crop yields, and how these relationships are affected by farm management, weather, and different crops. Models to predict correlations between individual soil properties of interest, i.e., yield-limiting factors, and EC_a are being developed (Lesch and Corwin, 2003). Such models are important for identifying the geographic extent to which specific applications of EC_a technology can be appropriately applied.

References

Corwin, D. L., and J. D. Rhoades. 1982. An improved technique for determining soil electrical conductivity-depth relations from above-ground measurements. *SSSA J.* 46: 517-520.

Corwin, D. L., S. M. Lesch, P. J. Shouse, R. Soppe, and J. E. Ayars. 2003. Identifying soil properties that influence cotton yield using soil sampling directed by apparent soil electrical conductivity. *Agron. J.* 95(2): 352-364.

Dalton, F. N. 1987. Measurement of soil water content and electrical conductivity using time-domain reflectometry. In *Proc. International Conference on Measurement of Soil and Plant Water Status*, 95-98. Logan, Utah: Utah State University.

Dalton, F. N., W. N. Herkelrath, D. S. Rawlins, and J. D. Rhoades. 1984. Time domain reflectometry: Simultaneous measurement of soil water content and electrical conductivity with a single probe. *Science* 224: 989-990.

Dasberg, S., and F. N. Dalton. 1985. Field measurement of soil water content and bulk electrical conductivity with time-domain reflectometry. *SSSA J.* 49: 293-297.

Doran, J. W. 2002a. Soil health and global sustainability: Translating science into practice. *Agric. Ecosyst. Environ.* 88(2): 119-127.

Doran, J. W. 2002b. Soil health: Agent of sustainable management and environmental remediation. In *Innovative Soil-Plant Systems for Sustainable Agricultural Practices*, 184-194. I. Unver, ed. Paris, France: Organization of Economic Cooperative Development.

Eghball, B., and J. F. Power. 1999. Phosphorus- and nitrogen-based manure and compost application: Corn production and soil phosphorus. *SSSA J.* 63(4): 895-901.

Eigenberg, R. A., and J. A. Nienaber. 1999. Soil conductivity map differences for monitoring temporal changes in an agronomic field. ASAE Paper No. 993173. St. Joseph, Mich.: ASAE.

Eigenberg, R. A., R. L. Korthals, and J. A. Nienaber. 1996. Electromagnetic survey methods applied to agricultural waster sites. ASAE Paper No. 963014. St. Joseph, Mich.: ASAE.

Eigenberg, R. A., J. W. Doran, J. A. Nienaber, and B. L. Woodbury. 2000. Soil conductivity maps for monitoring temporal changes in an agronomic field. In *Proc. 8th Int. Symp. on Animal, Agricultural, and Food Processing Wastes*, 249-265. CIGR.

Eigenberg, R. A., J. W. Doran, J. A. Nienaber, R. B. Ferguson, and B. L. Woodbury. 2002. Electrical conductivity monitoring of soil condition and available N with animal manure and a cover crop. *Agric. Ecosyst. Environ.* 88(2): 183-193.

Ferguson, R. B., and J. A. Nienaber. 2000. Composted beef feedlot manure application impacts on nitrogen and phosphorus accumulation and movement in soil. In *Proc. 8th Int. Symp. on Animal, Agricultural, and Food Processing Wastes*, 719-727. CIGR.

Fritz, R. M., D. D. Malo, T. E. Schumacher, D. E. Clay, and C. G. Carlson. 1999. Field comparison of two soil electrical conductivity measurement systems. In *Proc. 4th Int. Conf. on Precision Agriculture*, 1211-1217. Madison, Wisc.: ASA, CSSA, and SSSA.

Gilbertson, C. B., J. R. Ellis, J. A. Nienaber, T. M. McCalla, and T. J. Klopfenstein. 1975. Properties of manure accumulations from Midwest beef cattle feedlots. *Trans. ASAE* 18(2): 327-330.

Harmel, R. D., A. L. Kenimer, H. A. Torbert, and S. W. Searcy. 2004. Runoff water quality impact of variable-rate nitrogen application. *Precision Agric.* 5(3): 247-261.

Johnson, C. K., J. W. Doran, H. R. Duke, B. J. Wienhold, K. M. Eskridge, and J. F. Shanahan. 2001. Field-scale electrical conductivity mapping for delineating soil condition. *SSSA J.* 65(6): 1829-1837.

Johnson, C. K., K. M. Eskridge, B. J. Wienhold, J. W. Doran, G. A. Peterson, and G. W. Buchleiter. 2003a. Using electrical conductivity classification and within-field variability to design field-scale research. *Agron. J.* 95(3): 602-613.

Johnson, C. K., D. A. Mortensen, B. J. Wienhold, J. F. Shanahan, and J. W. Doran. 2003b. Site-specific management zones based upon soil electrical conductivity in a semiarid cropping system. *Agron. J.* 95(2): 303-315.

Johnson, C. K., R. A. Drijber, B. J. Wienhold, S. F. Wright, and J. W. Doran. 2004. Linking microbial-scale findings to farm-scale outcomes in a dryland cropping system. *Precision Agric.* 5(4): 311-328.

Kitchen, N. R., K. A. Sudduth, and S. T. Drummond. 1999. Soil electrical conductivity as a crop productivity measure for claypan soils. *J. Prod. Agric.* 12: 607-617.

Lark, R. M., and J. V. Stafford. 1997. Classification as a first step in the interpretation of temporal and spatial variation of crop yield. *Annals Appl. Biol.* 130: 111-121.

Larson, W. E., and P. C. Robert. 1991. Farming by soil. In *Soil Management for Sustainability*, 103-112. R. Lal and F. J. Pierce, eds. Ankeny, Iowa: Soil Water Conservation Society.

Lesch, S. M., and D. L. Corwin. 2003. Using the dual-pathway parallel conductance model to determine how different soil properties influence conductivity survey data. *Agron. J.* 95(2): 365-379.

McKenzie, R. C., W. Chomistek, and N. F. Clark. 1989. Conversion of electromagnetic inductance readings to saturated paste extract values in soils for different temperature, texture, and moisture conditions. *Canadian J. Soil Sci.* 69: 25-32.

Norman, D. W., L. E. Bloomquist, S. G. Freyenberger, D. L. Regehr, B. W. Schurle, and R. R. Janke. 1998. Farmers' attitudes concerning on-farm research: Kansas survey results. *J. Nat. Resour. Life Sci. Educ.* 27: 35-41.

Ranjan, R. S., T. Karthigesu, and N. R. Bulley. 1995. Evaluation of an electromagnetic method for detecting lateral seepage around manure storage lagoons. ASAE Paper No. 952440. St. Joseph, Mich.: ASAE.

Rhoades, J. D., N. A. Manteghi, P. J. Shouse, and W. J. Alves. 1989. Soil electrical conductivity and soil salinity: New formulations and calibrations. *SSSA J.* 53: 433-439.

Smith, J. L., and J. W. Doran. 1996. Measurement and use of pH and electrical conductivity for soil quality analysis. In *Methods for Assessing Soil Quality*, 169-185. SSSA Spec. Publ. 49. J. W. Doran and A. J. Jones, eds. Madison, Wisc.: SSSA.

Stanford, G., and S. J. Smith. 1972. Nitrogen mineralization potential of soils. *SSSA Proc.* 36: 465-472.

Sudduth, K. A., S. T. Drummond, and N. R. Kitchen. 2001. Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. *Comput. Electron. Agric.* 31(3): 239-264.

Topp, G. C., J. L. Davis, and A. P. Annan. 1980. Electromagnetic determination of soil water content: measurement in coaxial transmission lines. *Water Resour. Res.* 16: 574-582.

Veris Technologies. 2003. Sensors and controls for soil-specific agriculture. Salina, Kansas: Veris Technologies, Inc. Available at: www.veristech.com. Accessed 27 March 2003.

Wienhold, B. J., and Z. Rui. 2001. Use of electrical conductivity to estimate N-mineralization contributions to crop N availability. In *Proc. 12th World Fertilizer Conference.* Beijing, China: Chinese Agricultural Academy of Sciences.

Williams, B. G., and D. Hoey. 1987. The use of electromagnetic induction to detect the spatial variability of the salt and clay contents of soils. *Australian J. Soil Res.* 25: 21-27.